Nonspherical Void Growth Theories

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This work is a continuation of our efforts to develop a nonspherical void growth model to be used in important U.S. Department of Defense (DoD) and Department of Energy (DOE) applications. An example of a problem of interest is HY-100 steels. Metallographic fractography shows that low concentrations of manganese sulfide (MnS) impurities have a significant role in the fracture of HY-100 steels [1]. Examination of spalled HY-100 samples reveal that the MnS impurities act as microvoid initiation sites necessary for ductile fracture to occur. The MnS impurities form, during the rolling process, into high-aspect ratio-aligned inclusions. The alignment is the origin of the orientation dependence observed in fracture. Consequently, to model the fracture occurring in these steels it is important to include the nonspherical shape and orientation of the MnS impurities. There are several candidate theories in the scientific literature that might provide a good beginning point to modeling the damage processes occurring in these steels and in this work we focus on Continuum Damage Mechanics (CDM) and Gologanu-Leblond-Devaux (GLD) theory [2]. Background literature on CDM can be found in Lemaitre and Chaboche [3]. On the other hand, GLD theory provides a useful description of a flow surface for a material containing axial-symmetric ellipsoidal voids subjected to axial-symmetric loading and provides an important extension of Gurson's work [4] on flow stress surfaces for materials containing spherical voids. In FY04 we merged CDM, Gurson, and GLD theories to introduce a flow surface for nonsymmetric ellipsoidal voids with nonaxial-symmetric loading. In the present analysis we compare the predictions of these theories.

Continuum Damage Mechanics is based on the conjecture that there exists an effective stress $\tilde{\sigma}$ defined such that the complete continuum mechanics of a damaged material can be described by invoking a corresponding set of constitutive equations, given for an undamaged material, but with the simple replacement, $\sigma \rightarrow \tilde{\sigma}$. This replacement includes, for example, the stresses appearing in inelastic constitutive equations. The second conjecture of CDM is that $\tilde{\sigma}$ is then simply the stress carried by the undamaged cross-sectional area and a damage variable D can be introduced that is the fraction of damaged to the total cross-sectional areas.

For prolate ellipsoidal voids (aligned with the z axis) the GLD flow surface has the form:

$$F_{GLD} = \frac{C}{Y^2}(\sigma_{zz} - \sigma_{xx} + \eta\sigma_h)^2 - 1 - qf^2 + 2qf \cosh\left[\frac{\kappa\sigma_h}{Y}\right] = 0$$

In the limit of aspect ratio, β, equaling one, the GLD flow surface becomes the Gurson flow surface. In these expressions $(\sigma_{xx}, \sigma_{yy}, \sigma_{zz})$ are the three normal components of the stress tensor, C, k, η and σ_h are complex functions of the void and unit cell ellipsoid eccentricities, and β. Y is the flow stress of the matrix material, q_0 is an adjustable material parameter (taken equal to unity here), and f is the void volume concentration. In this expression the flow stress of the voided material Σ is

$$\Sigma^2_{GLD} = Y^2\left(1 + qf^2 - 2qf \cosh\left[\frac{\kappa\sigma_h}{Y}\right]\right),$$

From CDM theory we can derive (omitting the details)

$$F_{CDM} = \left(\frac{\sigma_{xx}}{1-D_1} - \frac{\sigma_{yy}}{1-D_2}\right)^2 + \left(\frac{\sigma_{xx}}{1-D_1} - \frac{\sigma_{zz}}{1-D_3}\right)^2 + \left(\frac{\sigma_{zz}}{1-D_3} - \frac{\sigma_{yy}}{1-D_2}\right)^2 - 2(\Sigma/\alpha)^2 = 0.$$

where

$$\Sigma^2_{CDM} = (Y/\alpha)^2\left(1 + qf^2 - 2qf \cosh\left[\frac{3\tilde{p}}{2(Y/\alpha)}\right]\right),$$

and $\tilde{p}$ and α are functions of the damage fields.

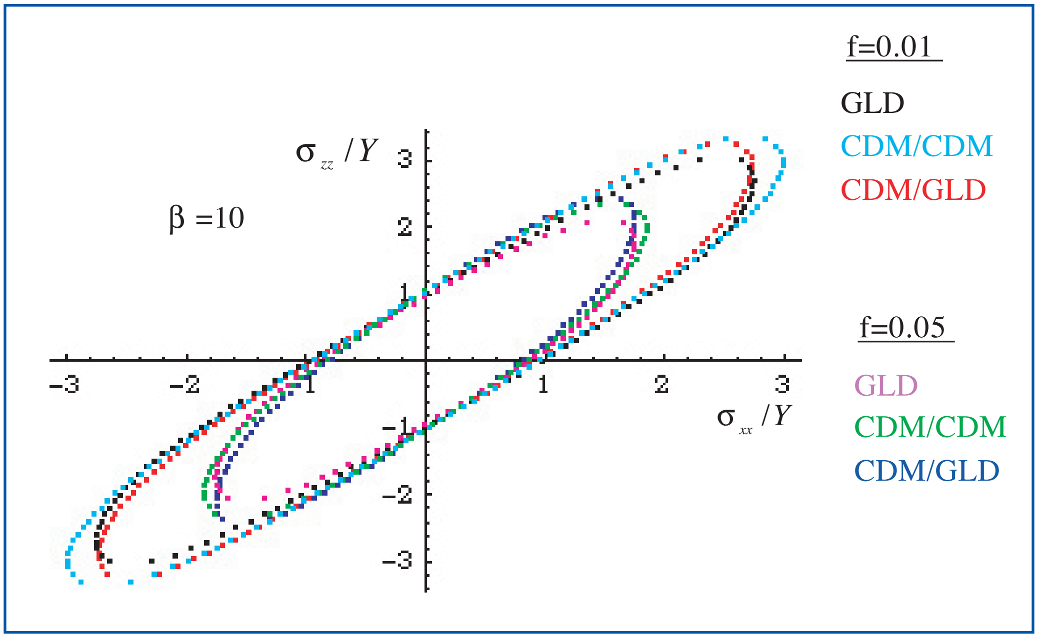

Figure 1*—*
Flow stress surfaces predicted by GLD, CDM, and CDM-GLD merged theories.

Figure 1 shows the flow stress surface, expressed in stress space. The flow stress surface is the locus of points $(\sigma_{xx}, \sigma_{zz})$, normalized by dividing by the matrix flow stress Y, that satisfy the condition $F = 0$. In F_{CDM} we can use two choices for Σ, namely the GLD and CDM forms, giving three flow surfaces to compare. Qualitatively and even quantitatively we see little difference between the three flow surfaces. Consequently, we assert that F_{CDM} compares well to F_{GLD} in this special case and moreover is general enough to handle nonaxial-symmetric prolate ellipsoids and arbitrary loads.

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